AN INVESTIGATION OF PRACTICAL HURRICANE SURGE FORECASTING

JOHN D. HAGUE

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John D. Hague

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
METEOROLOGY

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

The hurricane surge problem and the relative importance of the parameters involved are discussed. Three practical methods of forecasting the maximum height of the surge are explained, and tested for reliability on nine hurricanes covering the period 1954 through 1959. A tentative solution is presented for making a fourth method of height forecasting operational, and its merits relative to the first three methods are investigated. A quantitative method of forecasting the time of occurrence of the maximum surge is developed. This method is tested and the results are discussed.

The writer wishes to express his appreciation for the assistance and encouragement given him by Professor Glenn H. Jung of the U. S. Naval Postgraduate School in this study.

The author is also indebted to Mr. D. Lee Harris of the U. S. Weather Bureau for his suggestions and invaluable aid in supplying needed data upon which parts of this study were based.

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TABLE OF SYMBOLS AND ABBREVIATIONS

a	a constant combining a', ρ, & g
a'	a constant
B	a constant
b	a constant
C_T	speed of movement of a hurricane
CKH	"Conner, Kraft, and Harris"
D	decay distance
d	depth where waves "feel bottom"
F	true length of the fetch
F_R	fetch due to radial size of a hurricane
g	acceleration due to gravity
h	total setup due to the wind
h_{max}	maximum storm surge height (Conner, Kraft, and Harris)
h_{ext}	extreme storm surge height (Hoover)
K	a constant of proportionality
NHRP	"National Hurricane Research Project"
p_o	lowest central pressure in a hurricane
p_n	pressure at the edge of a hurricane
Δp^*	intensity of the storm
R	radial distance from the center of a hurricane (Francis, [3], uses the symbol "r")
R_{00}	radius of hurricane out to 1000 mb isoline
r	dynamic amplification factor
S	distance between the shore and the 50-fathom depth contour
T_D	period at end of decay
T_F	significant period of waves emitted at the fetch

t_d travel time

t'_{min} minimum duration

V_{max} maximum wind speed

W_p width of continental shelf along path of a hurricane

γ max storm surge height (Kajiura)

θ relative storm surge potential

ρ constant density of water

1. BACKGROUND

1.1 Introduction.

The rise in sea level associated with the passage of a hurricane accounts for the largest portion of all the damage and loss of life attributed to such storms [2, 6, 11]. The relative importance of this part of the overall hurricane problem has been known for some time, but it has only been within the past five or six years, since the very destructive Atlantic coast storms of 1954 and 1955, that intensive studies have been conducted in the United States to obtain practical methods of predicting the behavior of the sea along the coast during the passage of a hurricane.

1.2 Local Effects.

The problem of deriving any reasonably accurate prediction methods is greatly complicated by the very important effects of local topography, both above and below the mean water level. These local effects take the form of extra high water at the heads of converging bays and at exposed points, lower levels where bays and estuaries are wide [5], and sometimes violent oscillations of the water levels along the coast for long periods after the passage of a storm.

If these local effects are considered in a forecasting technique, then the area over which the method can be used is greatly reduced. Some "small-area" techniques have been developed, such as Wilson's technique for New York Bay [15]; however, due to the limited application of such methods, area-wise, they were not considered in this study.

Most prediction techniques have attempted to eliminate local effects as much as possible and can therefore be used over long stretches of coastline. For the purposes of this paper only these "wide-area" tech-

niques will be discussed.

1.3 Coastal Water Levels.

There are three fairly distinct reactions of the sea level as the result of a hurricane which crosses the coast. These are shown in Figure 1.

The forerunner is a very gradual rise in sea level which occurs a few days before the arrival of a hurricane, when it is still more than 200 miles from the coast. This build-up can, under certain conditions, cause flooding of a low-lying coast; however, this is not normal.

Following the forerunner, and within several hours of the passage of the hurricane, there is a very rapid rise in the water level. This is the storm surge which can be as high as eight to ten feet above the normal water level.

After the storm surge reaches its peak the water drops rapidly towards its normal level, but often "over-shoots" this mark; the water level hits a low point, builds up again, and continues to oscillate for a period of time. This is the resurgence which appears to be due to the free motion of water as it returns to its normal level [10]. In closed bays and estuaries this oscillation of the water can become even higher than the storm surge, and under such local conditions it can become a very serious problem; however, the resurgence is usually of small magnitude along the open coast.

Since the forerunner and the resurgence normally are not very destructive, the present state of prediction of high water levels is generally confined to the storm surge. Accordingly the remainder of this paper will deal only with the desired parameters relating to the storm surge.

Figure 1. WATER LEVELS DURING PASSAGE OF A HURRICANE

1.4 Storm Surge Definition.

The meaning of "storm surge" used in connection with this study is given by the definition of the National Hurricane Research Project of the U.S. Weather Bureau [6]. In this interpretation the storm surge is the actual water level less the astronomical tide and secular anomolies in the sea level. Figure 2 shows the effects of these three components on the actual water level for a general case.

The astronomical tide is the familiar diurnal or semi-diurnal change in sea level which can be obtained from tide tables. Generally the range of the astronomical tide is greater on the Atlantic coast than on the Gulf coast; however, it is of great importance in both cases due to the lower land elevations in the Gulf area. The astronomical tide becomes an important factor through its phase relationship with the storm surge. If the surge occurs when the astronomical tide is low, the actual water level may not be high enough to cause much harm; however, if the surge occurs at high tide, extremely high water levels may result with correspondingly large damage along the coast. If the forecaster knows when to expect the storm surge component, he can determine its phase relationship with the astronomical tide.

In the absence of a storm the secular anomoly is the difference between the astronomical tide and the actual tide, or essentially the level of the water that the tide table does not account for. It can amount to a foot or more in height and usually lasts for several weeks at a time. The present method for determining this anomoly requires the forecaster to be familiar with the predicted and actual tides for a period of a week preceeding the forecast time. He then makes a qualitative estimate of the anomoly from the differences between these

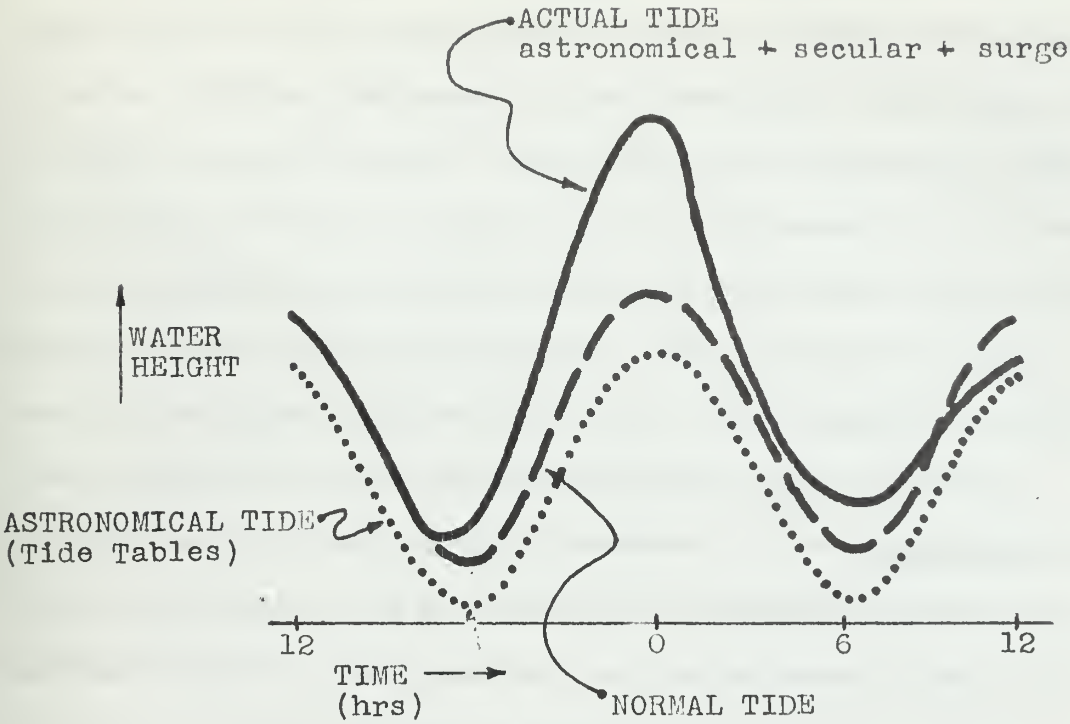

Figure 2. ACTUAL TIDE COMPONENTS

two quantities. A program has recently been established by the U. S. Weather Bureau in cooperation with the Coast and Geodetic Survey whereby remote recording tide gages have been installed at many Atlantic and Gulf Coast weather stations. These stations are provided with predictions of the astronomical tide and in turn they transmit the difference between the actual and predicted values along with their synoptic reports. When the program is fully operational a central office will apply an averaging technique to determine the final secular anomoly, which will then be available for more closely predicting actual tide levels.

The final, and most important component, is the storm surge itself. This is the change in the sea level that is the direct result of the hurricane high winds, low pressures, and the additional piling up of water near the shore by breaking waves.

1.5 Storm Surge Parameters.

In order to promulgate a satisfactory warning with regard to the high waters associated with a hurricane, it would be necessary for the forecaster to describe the distribution of water levels along the coast, the time when the water would reach its maximum height, and the duration of the high water. This problem can be broken down into the forecasting of five different parameters involving the storm surge.

These are:

1. The maximum height.
2. The location of the maximum height.
3. The lateral distribution of the surge along the coast.
4. The time that the maximum surge occurs.
5. The duration of the surge.

Figure 3 shows these parameters with values for a very general "average"

case.

The most important surge parameter is the maximum height that it will reach, since the other parameters will have little meaning otherwise. This is the only parameter quantitatively predictable at the present time.

Once that the maximum surge has been predicted, the forecaster would next be interested in knowing the time that the maximum would occur. A prediction of this parameter would not only allow timely action to be taken to protect lives and property; but, even more important, it would permit correct phasing of the surge with the astronomical tide so that the actual water level could be obtained more accurately. At present there are only qualitative rules to guide the forecaster in the prediction of the time of the maximum surge.

The forecaster would also be interested in the remaining three parameters, and again he would have to turn to qualitative rules. This study has not considered these three parameters.

1.6 Purpose.

The remainder of this paper will deal with the two parameters, the height and the time of the maximum surge. The results of a comparative study of four different height forecasting methods will be given in Section 2, and Section 3 will deal with the formulation of a technique for quantitatively forecasting the time of maximum surge.

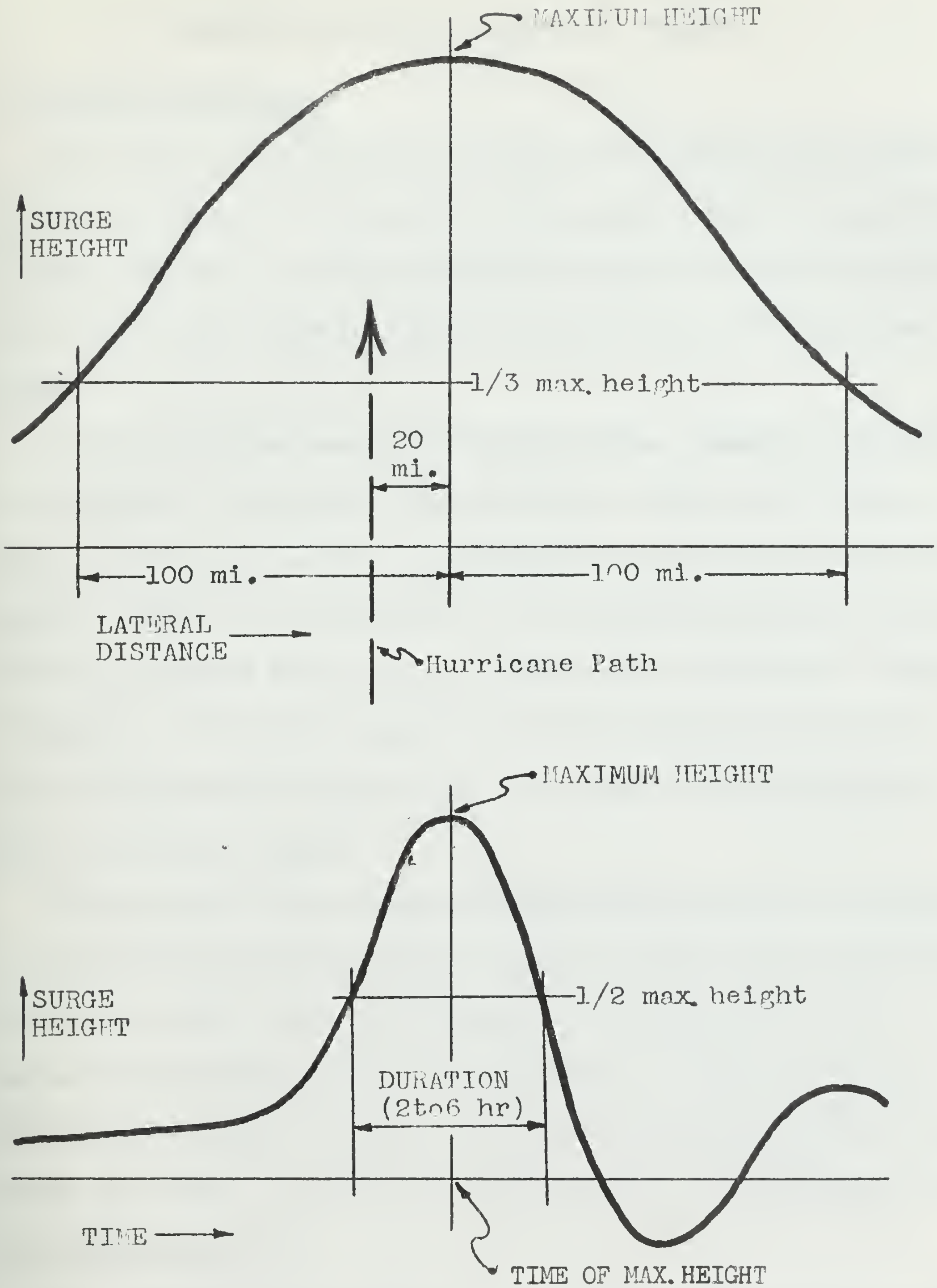

Figure 3. GENERAL SURGE PROFILES

2 EVALUATION OF HEIGHT FORECASTING METHODS

2.1 Methods of Approach.

The problem of forecasting the height of the maximum surge resulting from the passage of a cyclonic storm has been studied for some time throughout the world. For many years only a strictly dynamic approach could be made since actual hurricane data were scarce and mostly unreliable.

Other than studies made in the United States, notable contributions to the dynamics of the storm surge problem have been made by Dutch, English, and Japanese writers. At present the application of strictly dynamical theory to the prediction of the surge associated with storms affecting the United States can not be made with reliability. However, the dynamics of the storm surge are still being studied and in the future this theoretical approach may be of great value to practical prediction of surge height.

In recent years there has been considerable interest in collection and analysis of hurricane data which could be of use in the development of empirical surge forecasting techniques. With these data some progress has been made toward the development of practical methods of forecasting the maximum height of the surge. The present methods available are all based on theoretical principles, but are empirically derived.

2.2 Methods Considered.

Four prediction techniques were considered to be evaluated in this study. The derivation and use of each of these methods is presented in Appendices I through IV.

The basic consideration in each of these methods is that the height of the maximum surge is proportional to the pressure gradient in the storm.

The first two methods use a pressure parameter alone, and the other methods supplement this with additional parameters.

The first practical forecast method to be published was developed by Conner, Kraft, and Harris in 1957 [2]. This method will be referred to as the "CKH method". Just a few months after the CKH method had been presented, Hoover published a method which was quite similar to the first, but based on additional data which had been analysed in a different manner [7]. In August of 1959 the U.S. Weather Bureau officially published "An Interim Hurricane Storm Surge Forecasting Guide" as one of the reports of the National Hurricane Research Project [6]. This forecasting technique, which will be referred to as the "NHRP method", adds a parameter which takes into account the depth of water over which the hurricane travels. The final technique that was considered in this study was published in December of 1959. It was developed by Kajiura of the Agricultural and Mechanical College of Texas [8]. In this method two parameters are added to the basic pressure parameter. One of these is a constant that depends on the location of the station where the maximum surge occurs. The second additional parameter introduced in this method is the dynamic amplification factor. Since the method, as presented, does not give any rules for picking a value of the dynamic amplification factor in a particular storm situation, the first investigation in this study tested each storm for three values over the possible range of this factor as indicated by Kajiura.

2.3 Data Used.

In studying the various prediction techniques it was noted that different authors had assigned different numerical values to the same parameter for the same storm. This is probably due to the fact that as

hurricane data have been continually processed and analysed, the values which are considered correct naturally have changed from time to time. The data used in this study for testing the various methods of surge height prediction were obtained from the Climatological Data Periodicals [12] and a series of Storm Surge Data Charts provided by Mr. D. Lee Harris of the U. S. Weather Bureau. Some data for Hurricane AUDREY were obtained from the National Hurricane Research Project Report No. 23 [4].

Nine hurricanes covering the period from 1954 through 1959 were considered in this study for testing the prediction techniques. These storms, the maximum height of the surge, and the location of the maximum surge are listed in Table I.

2.4 Comparison of CKH, Hoover, and NHRP Methods.

The Kajiura method at present can not be considered as a practical forecasting technique since it still has not been determined how the on-the-spot forecaster would determine the dynamic amplification factor which is required in this method. For this reason the first three methods will be compared separately at first, while the Kajiura method results enter the comparison later.

The errors which resulted from applying the CKH, Hoover, and NHRP forecasting methods to the nine test storms are shown in Table I. The error is taken as the forecast height minus the actual height, so that a negative error indicates that the forecast was too small. Table II

HURRICANE Date	MAX.SURGE (ft.) Location	FORECAST ERRORS (ft.) CKH	Hoover	NHRP
CAROL Aug. '54	8.3 Newport, R. I.	+0.1	-0.1	-0.1
EDNA Sept. '54	4.9 Woods Hole, Mass.	+5.3	+5.9	+4.8
HAZEL Oct. '54	4.9 Morehead City, N. C.	+7.4	+8.7	+7.7
CONNIE Aug. 3-14 1955	4.4 Hampton Roads, Va.	+4.3	+4.4	+4.2
DIANE Aug. 7-21 1955	3.1 Wilmington, N. C.	+1.9	+0.8	+2.0
IONE Sept. '55	3.6 Morehead City, N. C.	+5.1	+5.2	+5.1
GRACIE Sept. '59	8.3 Charleston, S. C.	-3.3	-4.3	-3.1
FLOSSY Sept. '56	3.0 Bayou Rigaud, La.	+2.5	+3.6	+2.4
AUDREY June '57	12.1 Cameron, La.	-2.8	-1.3	-2.3

ERROR = Forecast - Actual

Table I. CKH, HOOVER, AND NHRP HEIGHT FORECAST ERRORS

shows these results tabulated according to how well each method forecast for each storm.

The NHRP method clearly seems to be the most reliable of these three forecasting techniques. Although both the CKH and the Hoover methods forecast the same number (3) of storms with minimum error, the CKH technique seems to be the more consistently reliable, achieving second place in the forecast of five storms.

Although, for certain storms, noteably HAZEL, the error is quite large, it should be noted (Table I) that all three of these methods forecast nearly the same height of maximum surge for each storm. The largest difference for any one storm was only a foot and a half, for hurricane AUDREY.

2.5 Kajiura Method.

As a first test, the Kajiura method was applied to each storm using three values of the dynamic amplification factor, r. The errors which resulted from this test are shown in Table III. When compared with the results obtained from the first three methods (Table I), this prediction technique appears to be much better.

An investigation of the dynamic amplification factor was conducted in order to determine whether the good results obtained from the Kajiura method were due solely to the wide range of heights covered by using values of r from 1.0 to 2.0. The dynamic amplification factor has been determined for a theoretical one-dimensional storm model by Reid [10] and graphed by Kajiura. This graph is reproduced in Figure 4. Kajiura has pointed out that the values of r for a two-dimensional model will be a little smaller than those shown in the graph.

In order to enter the graph of the dynamic amplification factor,

FORECAST METHOD	1st PLACE (fcst. with min. error)	2nd PLACE	3rd PLACE (fcst. with max. error)
CKH	CAROL HAZEL IONE	EDNA CONNIE DIANE GRACIE FLOSSY	AUDREY
Hoover	CAROL DIANE AUDREY	IONE	EDNA HAZEL CONNIE GRACIE FLOSSY
NHRP	CAROL EDNA CONNIE IONE GRACIE FLOSSY	HAZEL AUDREY	DIANE

Table II. CKH, HOOVER, AND NHRP METHOD PLACES

HURRICANE	FORECAST ERRORS (ft.)		
	r = 1.0	r = 1.5	r = 2.0
CAROL	-4.5	-2.5	-0.7
EDNA	-0.1	+2.4	+4.7
HAZEL	+3.5	+7.8	+11.9
CONNIE	+1.4	+4.4	+7.2
DIANE	+0.1	+1.7	+3.2
IONE	+2.2	+5.1	+8.0
GRACIE	-5.1	-3.5	-1.9

Table III. KAJIURA HEIGHT FORECAST ERRORS, r = 1.0, 1.5, & 2.0

the width of the shelf and the scale of the storm have to be known. In this study the width of the shelf was taken as the distance that the hurricane travelled over the continental shelf. The scale of the storm is essentially the fetch of the hurricane winds. As an approximation to the fetch the average radius of the hurricane out to the 1000 mb isoline was chosen. Using these values, as shown in Table IV, the amplification factors for the one-dimensional case were determined from the graph of Figure 4.

Next a hindcasting technique was applied to the Kajiura formula for forecasting the height to determine the actual value of r for each case. The actual and one-dimensional values of the amplification factor were next compared and it was determined that the one-dimensional values were 0.8 units too large in the mode. Using the same curve as presented for the one-dimensional case, the r scale was shifted 0.8 units as a rough approximation to the dynamic amplification factor for the actual storm case.

Using the scale-shifted graph, r was determined, and a forecast of the maximum surge height was made for each of the seven applicable storms. The errors that resulted from forecasts made using the scale-shifted graph are tabulated along with the errors that resulted from the first three methods, in Table V. These results obtained from using the Kajiura method with the scale-shifted graph for amplification factor are considered along with the results of the other three methods in Table VI, which shows how well each of the four methods predicted the height for each of the seven Atlantic coast hurricanes. These tables would seem to indicate that the Kajiura method is the best of those tested.

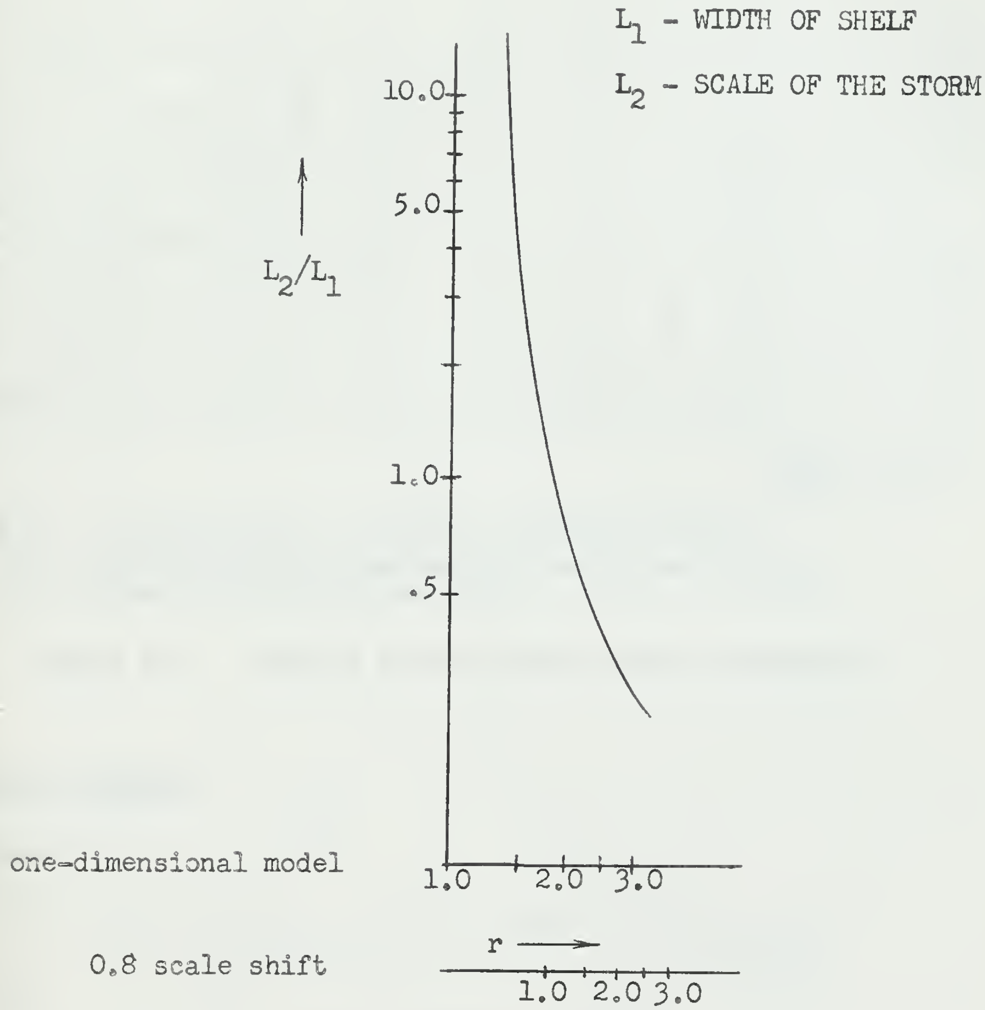

Figure 4. DYNAMIC AMPLIFICATION FACTOR GRAPH

STORM	$\overline{R_{00}}$ (L_2)	W_p (L_1)	$\overline{R_{00}}/W_p$ (L_2/L_1)	r 1 dim.	r (hind-cast)	r diff.
CAROL	1.6	3.2	0.5	2.3	2.16	+0.14
EDNA	2.3	2.1	1.1	1.8	1.01	+0.79
HAZEL	1.2	1.3	0.9	1.9	0.58	+0.32
CONNIE	2.0	1.5	1.3	1.75	0.75	+1.0
DIANE	1.0	0.9	1.1	1.8	0.97	+0.83
IONE	0.5	1.0	0.5	2.3	0.62	+1.68
GRACIE	0.9	1.3	0.7	2.0	2.60	-0.60
						mode ~ 0.8

$\overline{R_{00}}$ = average radius of 1000 mb isoline (° Lat.)
W_p = width of shelf along path of hurricane (° Lat.)
r = dynamic amplification factor

Table IV. DYNAMIC AMPLIFICATION FACTOR ADJUSTMENT

HINDCAST EXAMPLE:

Kajiura,

$$\zeta = r\, a\, \Delta p^* ; \quad \Delta p^* = 0.55\ (1015 - p_o)$$

$$\zeta = r\, a\, [\, 0.55\ (1015 - p_o)\,]$$

$$r = \frac{\zeta}{a\,[\,0.55\,(1015 - p_o)\,]} ; \quad \begin{array}{l} \text{Region I: } a = 0.14 \\ \text{Region II: } a = 0.2 \end{array}$$

Hurricane EDNA:

$$r = \frac{4.9}{0.14\,[0.55\,(1015 - 952)]} = 1.01$$

HURRICANE	FORECAST ERRORS (ft.)			
	CKH	Hoover	NHRP	Kajiura
CAROL	+0.1	-0.1	-0.1	-2.5
EDNA	+5.3	+5.9	+4.8	-0.1
HAZEL	+7.4	+8.7	+7.7	+3.7
CONNIE	+4.3	+4.4	+4.2	+1.4
DIANE	+1.9	+0.8	+2.0	+0.1
IONE	+5.1	+5.2	+5.1	+5.1
GRACIE	-3.3	-4.3	-3.1	-4.7

Table V. HEIGHT FORECAST ERRORS
CKH, HOOVER, NHRP, and KAJIURA (r scale shifted)

FORECAST METHOD	1st PLACE	2nd PLACE	3rd PLACE	4th PLACE
CKH	CAROL IONE	HAZEL GRACIE	EDNA CONNIE DIANE	
Hoover	CAROL	DIANE IONE	GRACIE	EDNA HAZEL CONNIE
NHRP	CAROL IONE GRACIE	EDNA CONNIE	HAZEL	DIANE
Kajiura	EDNA HAZEL CONNIE DIANE IONE	CAROL		GRACIE

TABLE VI. METHOD PLACES
CKH, HOOVER, NHRP, and KAJIURA (r scale shifted)

2.6 Height Forecasting Conclusions.

It is obvious that the final test of the Kajiura method is far from being unbiased since the selection of the dynamic amplification factor, r, was based on the actual maximum surge height for the storms considered. The results can not lead to a definite conclusion that the Kajiura method is more reliable than the others. However, it is believed that further study of this method would be well worth-while. The scale-shifted graph for determination of r that was used in this study is at best only a crude approximation to the actual storm case, since the only change from the one-dimensional model curve is the shift of the r scale, and this is based on data from only seven hurricanes. An empirical study of this factor using more data probably would lead to an entirely different curve. It should be pointed out also that the measurement of the "scale of the storm" is extremely difficult. Further study should be made in this area with an aim toward defining this measurement or toward substituting a different parameter which would give desirable results.

With additional study, the Kajiura method could become an operational forecasting method which may be more accurate than the existing practical techniques. However, at the present time, it is believed the NHRP method is the most reliable for forecasting the height of the maximum surge.

3. A QUANTITATIVE TIME FORECASTING METHOD

3.1 Importance of Time Forecasting.

Once the practical forecaster has predicted the maximum height of the surge, he then would be interested in the time that the maximum surge would occur. As pointed out before, a knowledge of the time of the maximum surge would allow more opportune measures to be put into effect for the protection of life and property; it also would help the forecaster to correctly predict the phase of the surge with relation to the astronomical tide, therefore giving more nearly correct predictions of the actual water level. This study, therefore, has attempted to develop a simple, quantitative technique for forecasting the time of the maximum surge.

3.2 Development of the Technique.

For determining the time that the maximum surge would occur, it was first assumed that the surge was the result only of the wind-generated waves produced at the storm, and that the surge travelled at the group velocity of these waves. The basic procedure was to determine an effective fetch at the position of the hurricane; permit decay of these waves enroute to the coast and determine the resulting period after decay; and from this period, calculate the time that would elapse during travel over the decay distance.

The general technique suggested by Francis [3] was followed in developing a convenient measurement of the fetch. A simple circular hurricane model was adopted as shown in Figure 5. This model was divided into eight sectors, each of which can be considered as a fetch which emits waves in a direction depending on the orientation of the sector and the direction of movement of the storm. The 90° sector was chosen

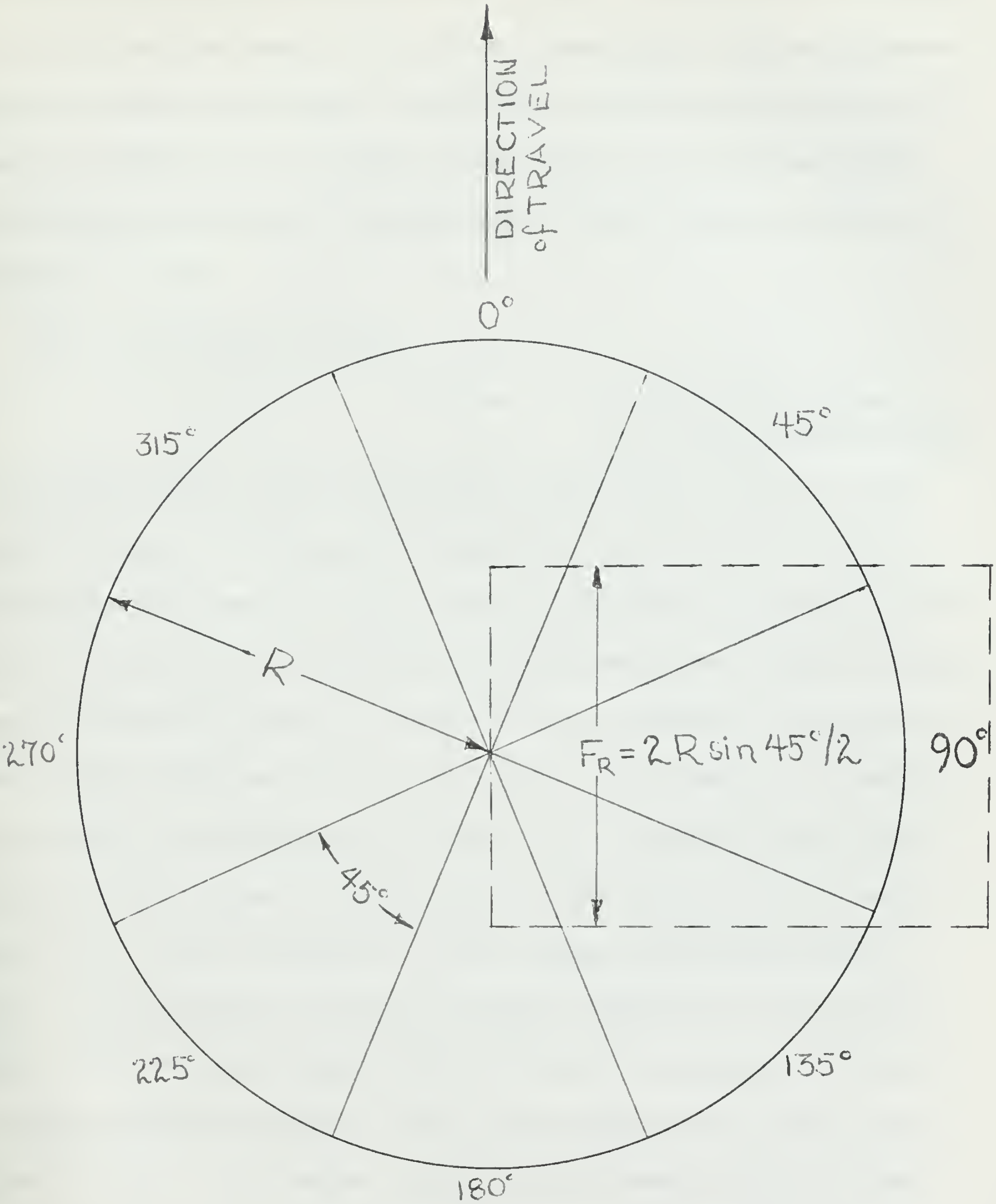

Figure 5. STORM MODEL

as the one from which the highest waves would be emitted, and the one that would have the most effect on the storm surge. This is in agreement with actual wave reports from numerous storms, and with the fact that the storm surge is normally to the right of the hurricane path. The fetch, at distance R[1] from the center of the storm is given by Francis [3] as:

(1) $$F_R = 2R \sin A/2$$

where: A = angular width of sectors ($A = 45^{\circ}$ for model chosen)

Francis has found, using Sverdrup-Munk relationships, that for wind speeds in excess of 40 knots the significant period of the waves is essentially the same for both the case of stationary and moving storms. (i.e. the same period is produced for all winds above 40 knots blowing over the same-sized fetch.) Therefore it was assumed in the development of this technique that the wind speed in the fetch was 40 knots. In the actual forecasting case it would not be possible to tell where the wind speeds dropped below 40 knots, since seldom are there more than three or four simultaneous reports within the hurricane area. Based on some detailed wind field analysis conducted by Redfield and Miller [9] the area between 1000 and 1005 mb was chosen as the cut-off point for 40 knot winds. Both of these values were tested, using Wilson's [14] Ht-FT diagram (Figure 6), for several actual storms and the resulting periods were nearly identical. Since the 1000 mb isoline almost always appears in map analyses, this was selected as the basis for determining R, the radius of the storm in the calcula-

[1] Francis uses the symbol "r". "R" has been substituted in this study for the radius of the storm to avoid confusion with Kajiura's "r", the dynamic amplification factor.

tion of the fetch, F_R.

The model fetch which will give the necessary information with regard to the surge lies 90° to the right of the storm path. Over this fetch the wind speed is 40 knots, and the size of the fetch is determined by the distance from the center of the storm to the 1000 mb isoline.

The next problem was to show the relationships between the radius of the storm out to the 1000 mb isoline, R_{00}, the speed of movement of the storm, C_T, and the resulting significant periods, T_F.

A series of effective fetches was chosen to cover the possible range in the hurricane situation. The corresponding T_F, for a 40 knot wind blowing over the chosen effective fetches were determined from Wilson's Ht-FT diagram [14] which is inserted in this report as Figure 6.

The effective fetch, F', equals the true length of the fetch, F, plus the distance that the fetch has travelled due to the movement of the storm. The distance that the fetch has travelled is equal to the minimum duration, t'_{min}, times the speed of the storm. The resulting equation for the effective fetch is [3] :

(2) $$F' = F + t'_{min} C_T$$

This equation can be rearranged for the determination of F, knowing F', t'_{min}, and C_T. The minimum duration was determined from the Ht-FT diagram; and several values of the speed of the storm, C_T, were chosen, covering the range from 0 to 35 knots. With these values and the previously-chosen values of F' the fetches were calculated. The fetch, F, was taken as F_R in equation (1) and the associated values of R were calculated. A graph of R vs. T_F for the various storm speeds was prepared.

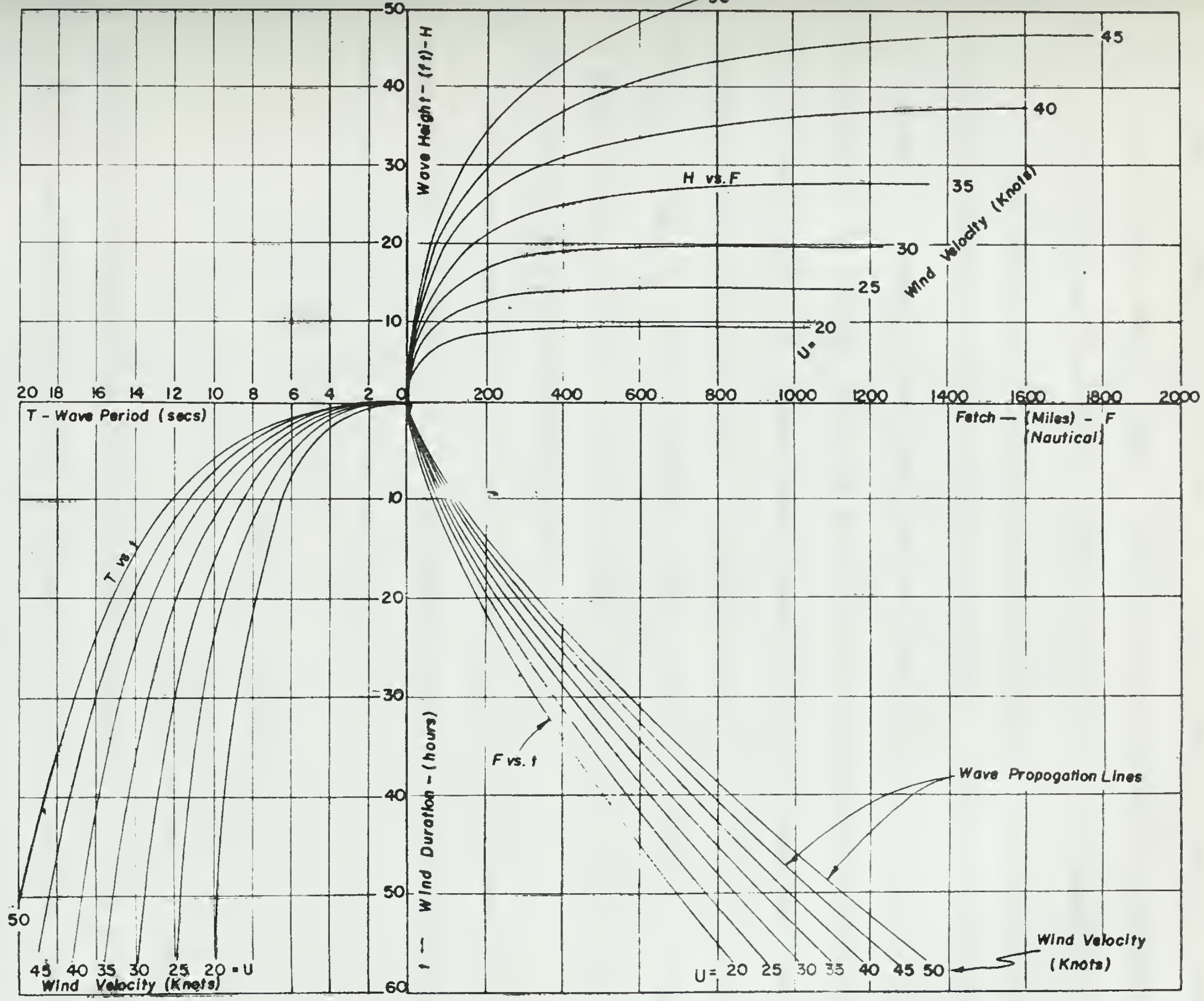

Figure [illegible]. Ht – FT DIAGRAM FOR FORECASTING WIND-GENERATED WAVES [illegible]

This graph showed that there was not a large range of periods associated with the range in storm speeds. Since it was desirable to eliminate as many parameters as possible in order to simplify the forecasting procedure, a mean speed was chosen and the associated curve of R_{OO} vs. T_F was adopted to cover all speeds of storm movement. This curve is presented in Figure 7. These significant periods then had to be modified to account for decay of the waves from the end of the fetch into the coastline. The Bretschnieder [1] wave decay curves (Figure 8) were applied to various values of T_F for decay distances from 25 to 1000 n.mi. and the decay periods, T_D were calculated. The resulting values were drawn as a graph of R_{OO} vs. T_D for various decay distances, D. This graph was then transformed into nomogram form.

A second nomogram was drawn for the travel time of waves, which depends on the group velocity associated with the period at the end of the decay distance [1], from the formula:

$$t_d = .66\, D/T_D$$

where: t_d = travel time
D = decay distance
T_D = period at end of decay

Since these two nomograms had two common parameters, T_D and D, they could be combined easily. The combined t_d-D-T_D-R_{OO} nomogram is shown as Figure 9. If the assumption can be made that over the entire decay distance the waves travel in deep water, then the forecaster would not be interested in the value of the period, T_D. This assumption is particularly valid when the travel time in shallow water is small compared with the total. Therefore, another nomogram was drawn which is the same as that shown in Figure 9 except that T_D has been eliminated and the scale changed somewhat. This nomogram shown in Figure 10 is the

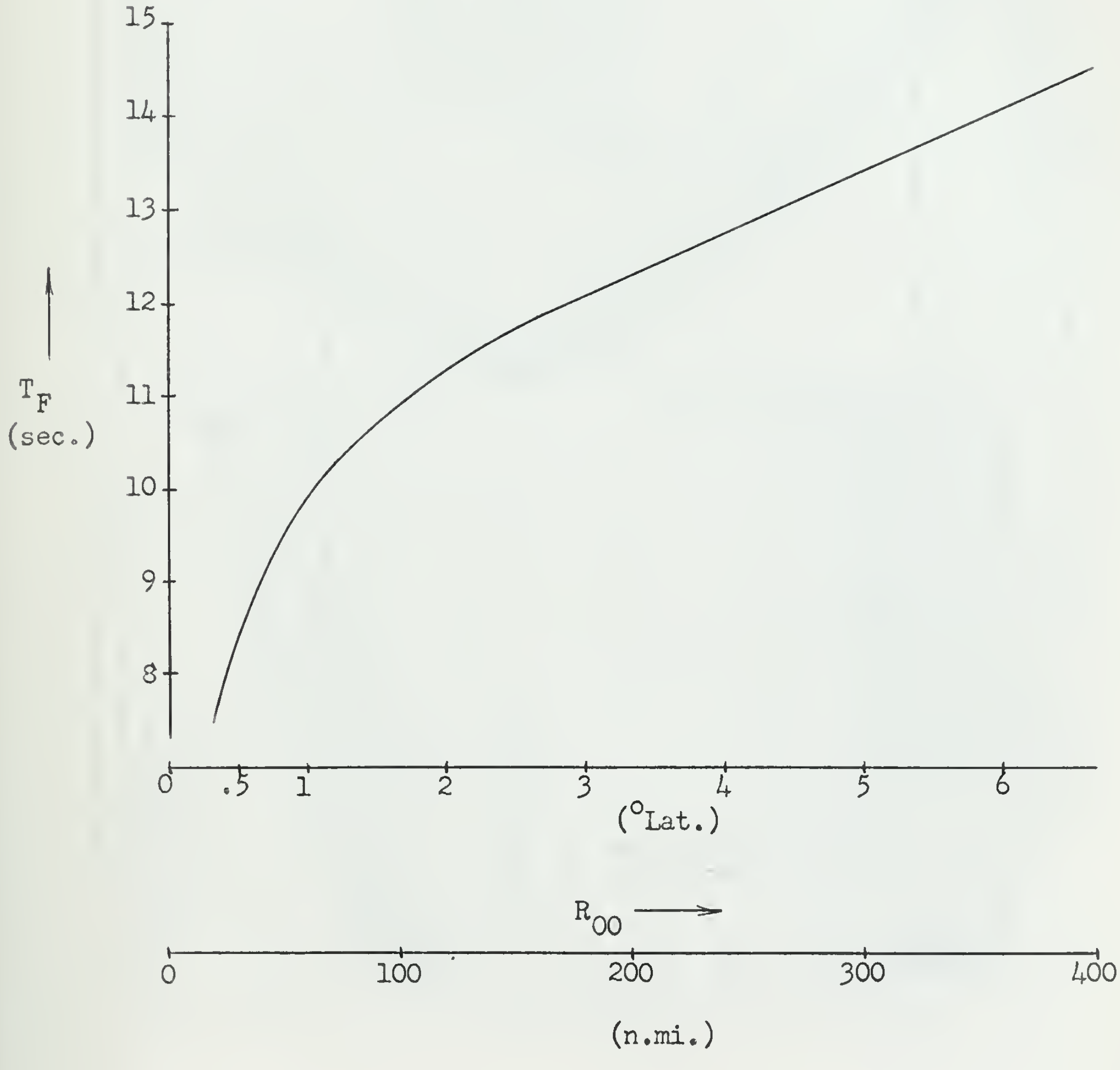

Figure 7. R_{00}- T_F GRAPH

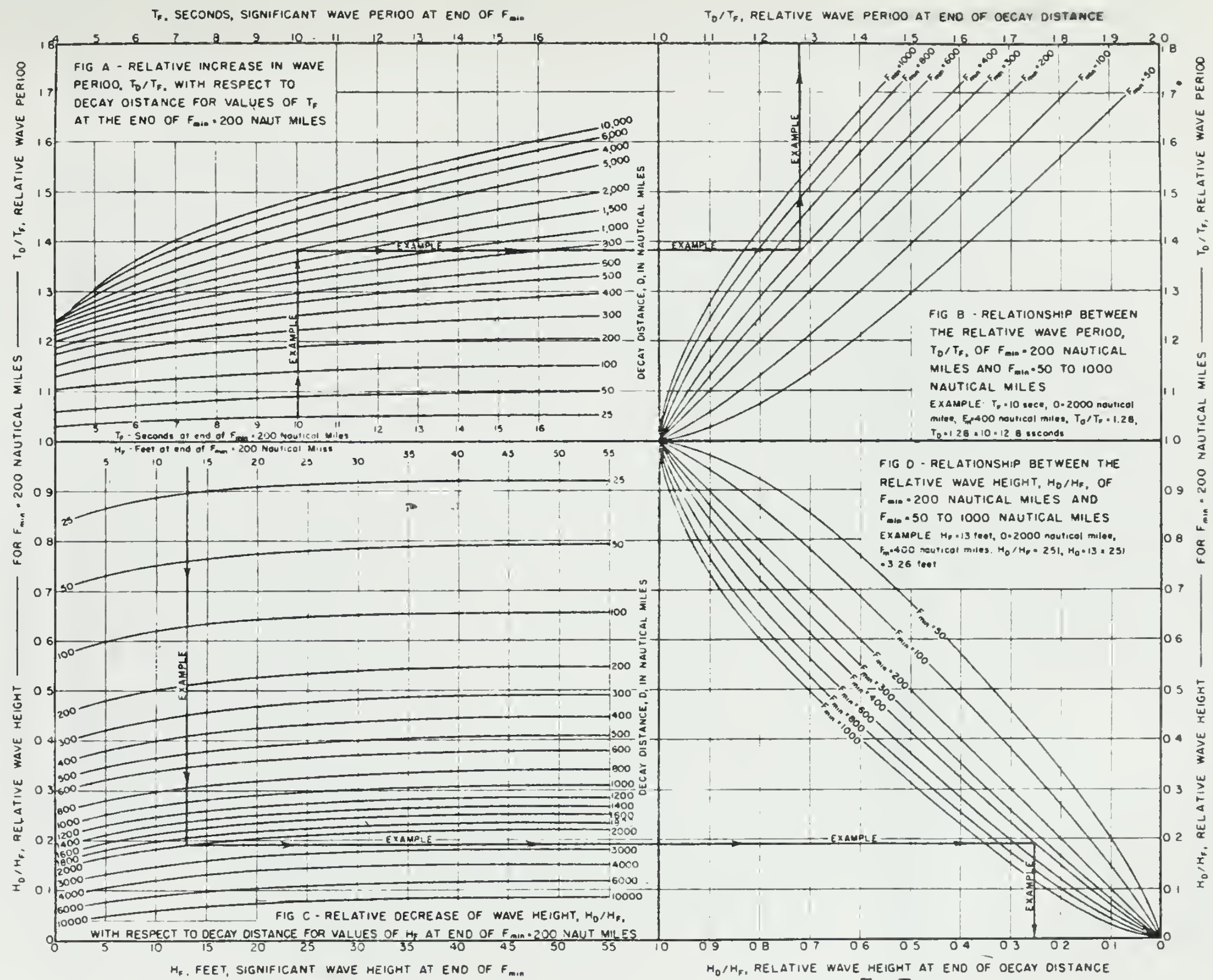

Figure 8. Forecasting curves for wave decay. [illegible]

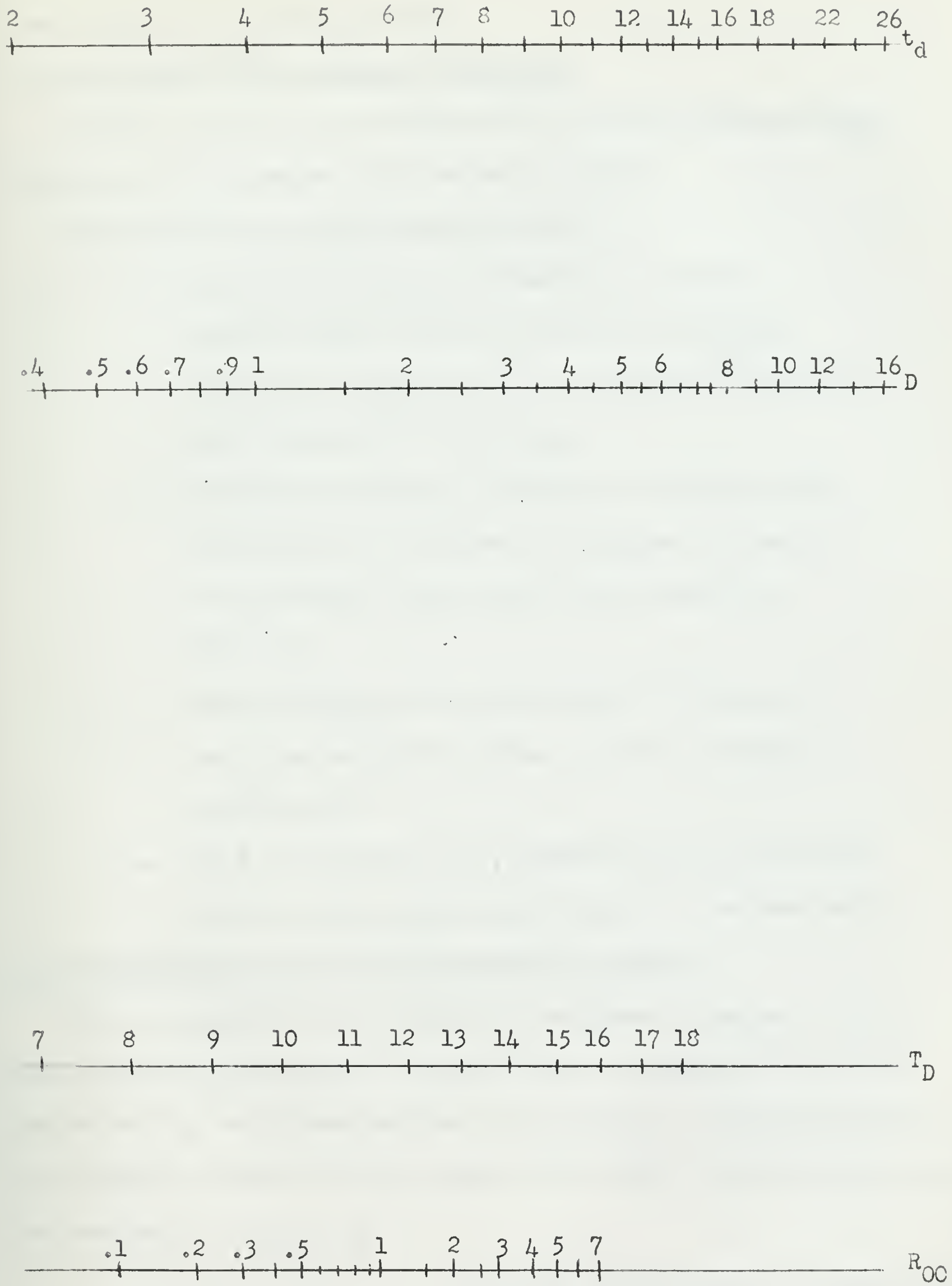

Figure 9. t_d-D-T_D-R_{OO} NOMOGRAM

final suggested forecasting diagram.

3.3 "Deep Water" Time Forecasting Procedure.

To make a forecast of the time that the maximum hurricane surge will occur, the forecaster would proceed as follows:

Using the latest synoptic hurricane plot;

1. Measure the distance, in degrees of latitude, from the center of the hurricane to the 1000-mb isoline in a direction 90° to the right of the forecast storm track. This is R_{00}.
2. Measure the distance, in degrees of latitude, from the position of the storm in the general direction of the forecast storm track to the coast line. This is D.
3. Enter the R_{00}-t_d-D nomogram (Figure 10) with the two values measured in steps 1. and 2. to obtain the time, t_d.
4. Add t_d to the time of the synoptic plot of the hurricane, to obtain the forecast time of the maximum surge.

3.4 "Deep-Shallow Water" Time Forecasting Procedure.

For the purposes of this study the usefulness of making a correction for wave travel close to the coast was investigated. To do this the period, T_D, was determined from the t_d-D-T_D-R_{00} nomogram (Figure 9) and the depth at which the waves would "feel bottom" was calculated from the formulas:

$$L_o = 5.12\,(T_D)^2$$

where: L_o = deep water wave length (ft)

$$d = \tfrac{1}{2} L_o$$

where: d = depth that waves feel bottom

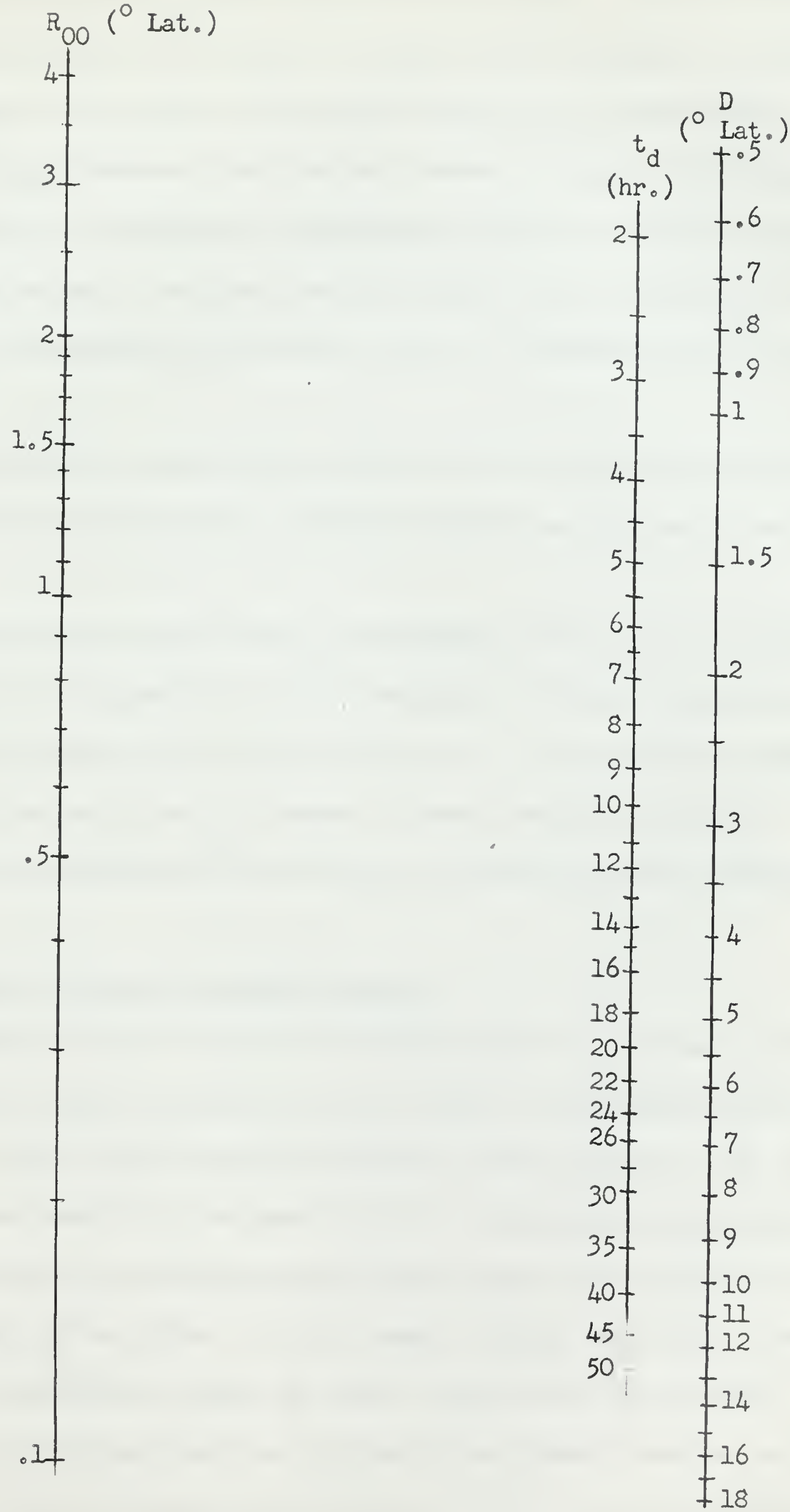

Figure 10. R_{00}-t_d-D NOMOGRAM

This depth was located on a chart along the storm path. From the position of the hurricane to this point the waves were considered to travel over deep water and the time was obtained directly from the nomogram. For the remaining distance, from the point where the waves feel bottom to the coastline, the waves were considered to travel in shallow water (i.e., as long waves). The time for this distance was determined by doubling the corresponding "deep-water" time, t_d, obtained from the nomogram.

The time for deep water travel and the time for shallow water travel were added and then the forecast time was obtained as previously described.

A correction for wave travel in intermediate water was not considered since one of the objectives in the development of this forecasting procedure was to keep it as simple as possible. It is seen that simply introducing a correction which assumes a sudden change from deep to shallow water has complicated the procedure and requires more "equipment" than before.

3.5 Evaluation of Time Forecasting Methods.

The Weather Bureau's Interim Forecasting Guide [6] gives a series of qualitative rules for prediction of the time of the maximum surge, based on the path of the hurricane relative to the coastline. All of the storms considered in this study fall into a catagory for which these rules indicate that the maximum surge occurs "within a few hours" of the closest passage of the storm. In this study, "within a few hours" was interpreted to be plus or minus two hours. The time of the closest passage of the storm was taken as the time of the lowest pressure as listed in the Climatological Data Periodicals [12] for the stations

where the maximum surge occurred. The results obtained from applying this qualitative technique are listed in Table VII.

Forecasts were also made considering that the surge travelled at the same speed as the storm. In this case the surge would arrive at the same time as the hurricane. Predictions of the time of the maximum surge based on this assumption are also listed in Table VII. The times that the hurricanes crossed the coast were obtained from the Storm Surge Data Charts, provided by Mr. D. Lee Harris, the Climatological Data National Summary [12] for Hurricane GRACIE, and the National Hurricane Research Project Report No. 23 [4] for Hurricane AUDREY.

Both the "deep water" and the "deep-shallow water" methods, previously described, were used to forecast the time of the maximum surge for the same nine hurricanes as previously used in the test of the height forecasting methods.

The storm sizes, R_{00}, and the storm tracks for 1954, 1955, and 1956 hurricanes were obtained from the Annual Tropical Storm Reports of the U. S. Navy Fleet Weather Central [13]. For 1957 and 1959 hurricanes the storm sizes were measured from the Facsimile Charts which had been transmitted by the U. S. Weather Bureau. Storm tracks for these latter hurricanes were obtained from the Climatological Data Periodicals [12]. The time of the maximum surge, for all storms except AUDREY and GRACIE, were obtained from the Storm Surge Data Charts provided by Mr. Harris. This last parameter for hurricane AUDREY was obtained from the National Hurricane Research Project Report No. 23 [4]. The time of the maximum surge for hurricane GRACIE was taken from the September 1959 Climatological Data National Summary [12].

For each hurricane considered, a time of the maximum surge was fore-

STORM	t_a	t_o	t_q	t_s
CAROL	31-1200	31-1040	31-0840 to 1240	31-1030
EDNA	11-1400	11-1353	11-1153 to 1553	11-1400
HAZEL	15-1300	15-1150	15-0950 to 1350	15-1200
CONNIE	12-2200	12-2145	12-1945 to 2345	12-2200
DIANE	17-1600	17-1030	17-0830 to 1230	17-1030
IONE	19-1000	19-0615	19-0415 to 0815	19-0600
GRACIE	29-1100	29-1316	29-1116 to 1516	29-1330
FLOSSY	24-0330	24-0145	23-2345 to 24-0345	24-0200
AUDREY	27-1100	27-0830	27-0630 to 1030	27-0830

t_a - actual time of the maximum surge

t_o - time of passage of lowest pressure at station of maximum surge

t_q - "qualitative" forecast time of maximum surge

t_s - "surge speed = storm speed" forecast time of maximum surge

Table VII. "QUALITATIVE" & "SURGE SPEED = STORM SPEED" FORECASTS OF TIME OF MAXIMUM SURGE

cast for every reported position within 1200 n.mi. of the coast line, for which data were available. The results of these forecasts using the "deep water" and "deep-shallow water" methods are tabulated in Tables VIII & IX. It can be seen that for most of the storms tested using the "deep water" method the forecast time approached the actual time from the early side with very few "late" forecasts. Using the "deep-shallow water" technique the approach of the forecasted times was the same, but many more "late" forecasts resulted when the storm was close to the coast.

The results obtained from all four of these techniques for forecasting the time of the maximum surge ("qualitative", "surge speed = storm speed", "deep water", and "deep-shallow water" methods) can be examined by looking at the errors that resulted from the application of each of them to the nine storms which were considered. These errors are shown in Table X. The error is taken here as the forecast time minus the actual time of the maximum surge; therefore a plus error indicates a late forecast.

Forecasts made using the qualitative rules bracketed the actual time in five out of the nine cases. Of course each of these forecasts cover a range of four hours which is somewhat undesirable. A comparison of the three remaining techniques, which give a single time for each forecast, show that the closest forecasts for more of the hurricanes (four out of nine) are obtained from assuming that the surge travels with the hurricane. The "deep water" method made the best forecasts for three of the storms, and the "deep-shallow water" method was closest for only two hurricanes. It should be pointed out that the forecasts made using the first two methods were based on actual hurricane data. If forecast

STORM time of max. surge	R_{00}	D	t	t_f	ERROR (fcst-actual)
CAROL	.6	12.2	27-0730	28-2230	-61.5
Aug. '54	.4	12.0	28-0730	29-2330	-36.5
31-1200	.7	12.0	29-0730	30-2130	-14.5
	1.6	10.3	30-0730	31-1100	- 1.0
	1.7	1.8	31-0730	31-1300	+ 1.0
EDNA	2.8	13.5	9-0730	10-1830	-19.5
Sept. '54	1.7	11.1	10-0730	11-1530	+ 1.5
11-1400	3.5	3.2	11-0730	11-1600	+ 2.0
HAZEL	1.2	13.3	13-1330	15-0330	- 9.5
Oct. '54	1.5	7.1	14-1330	15-1030	- 2.5
15-1300					
CONNIE	1.6	11.3	8-0730	9-1530	-78.5
Aug. '55	1.8	7.4	9-0730	10-0430	-65.5
12-2200	1.4	5.7	10-0730	11-0030	-45.5
	2.0	4.7	11-0730	11-2100	-26.0
	2.6	2.4	12-0730	12-1430	- 7.5
DIANE	.9	6.5	15-1330	16-1000	-30.0
Aug. '55	1.1	2.7	16-1330	16-2200	-18.0
17-1600					
IONE	.7	11.8	16-1330	18-0230	-31.5
Sept. '55	.4	8.1	17-1330	18-1730	-16.5
19-1000	.4	3.7	18-1330	19-0300	- 7.0

Table VIII. "DEEP WATER" FORECASTS OF TIME OF MAXIMUM SURGE (2 pages)

STORM time of max. surge	R_{00}	D	t	t_f	ERROR (fcst-actual)
GRACIE Sept. '59 29-1100	.6	7.2	26-1900	27-1900	-40.0
	.6	7.2	27-0100	28-0100	-34.0
	.8	7.4	27-0700	28-0700	-28.0
	.6	7.2	27-1300	28-1300	-22.0
	1.0	6.1	27-1900	28-1400	-21.0
	.8	5.8	28-0100	28-2000	-15.0
	.5	5.2	28-0700	29-0100	-10.0
	.9	5.1	28-1300	29-0500	- 6.0
	1.0	3.8	28-1900	29-0730	- 3.5
	1.1	2.3	29-0100	29-0830	- 2.5
	1.3	1.5	29-0700	29-1200	+ 1.0
FLOSSY Sept. '56 24-0330	.7	3.0	23-0730	23-1730	-10.0
	1.0	2.3	23-1330	23-2100	- 6.5
	1.4	1.2	23-2200	24-0200	- 1.5
	1.4	.6	24-0130	24-0330	0.0
AUDREY June '57 27-1100	.8	7.3	25-0730	26-0630	-28.5
	1.7	4.2	26-0730	26-2000	-15.0
	2.0	.4	27-0730	27-0900	- 2.0

R_{00} - radius of 1000 mb isoline ($^\circ$ lat.)
D - distance to point of max surge ($^\circ$ lat.)
t - synoptic time of hurricane (DTG local)
t_f - "deep water" forecast time of max surge

Table VIII. "DEEP WATER" FORECASTS OF TIME OF MAXIMUM SURGE (Continued)

STORM time of max. surge	SHALLOW WATER TRAVEL	t'_f	ERROR (fcst-actual)
CAROL	2.5	29-0830	-51.5
Aug. '54		30-0930	-26.5
31-1200		31-0730	- 4.5
		31-2130	+ 9.5
		31-1900	+ 7.0
EDNA	2.0	11-0130	-12.5
Sept. '54		11-2200	+ 8.0
11-1400		11-2230	+ 8.5
HAZEL	1.0	15-0830	- 4.5
Oct. '54		15-1430	+ 1.5
15-1300			
CONNIE	1.5	9-2100	-73.0
Aug. '55		10-1030	-59.5
12-2200		11-0630	-29.5
		12-0230	-19.5
		12-1930	- 2.5
DIANE	1.0	16-1400	-26.0
Aug. '55		17-0230	-13.5
17-1600			
IONE	1.0	18-0530	-28.5
Sept. '55		18-2200	-12.0
19-1000		19-0730	- 2.5

Table IX. "DEEP-SHALLOW WATER" FORECASTS OF TIME OF MAXIMUM SURGE (2 pages)

STORM time of max. surge	SHALLOW WATER TRAVEL	t'_f	ERROR (fcst-actual)
GRACIE Sept. '59 29-1100	1.0	27-2300	-36.0
		28-0500	-30.0
		28-1030	-24.5
		28-1700	-18.0
		28-1800	-17.0
		29-0000	-11.0
		29-0530	- 5.5
		29-0900	- 2.0
		29-1100	0.0
		29-1200	+ 1.0
		29-1600	+ 5.0
FLOSSY Sept. '56 24-0330	1.5	24-0000	- 3.5
		24-0300	- .5
		24-0600	+ 2.5
		24-0530	+ 2.0
AUDREY June '57 27-1100	2.0	26-1430	-20.5
		27-0300	- 8.0
		27-1030	- .5

t'_f - "deep-shallow water" forecast time of maximum surge (DTG local)

Table IX. "DEEP-SHALLOW WATER" FORECASTS OF TIME OF MAXIMUM SURGE (Continued)

STORM	ERROR (forecast - actual) t_q		t_s	t_f	t'_f
CAROL	+0.5	-3.5	-1.5	+ 1.0	+ 7.0
EDNA	+2.0	-2.0	0.0	+ 2.0	+ 8.5
HAZEL	+1.0	-3.0	-1.0	- 2.5	+ 1.5
CONNIE	+2.0	-2.0	0.0	- 7.5	- 2.5
DIANE	-3.5	-7.5	-5.5	-18.0	-13.5
IONE	-1.5	-5.5	-3.5	- 7.0	- 2.5
GRACIE	+4.5	+0.5	+2.5	+ 1.0	+ 5.0
FLOSSY	+0.5	-3.5	-1.5	0.0	+ 2.0
AUDREY	-0.5	-4.5	-2.5	- 2.0	- 0.5

t_q - "qualitative" forecast time of max. surge
t_s - "surge speed = storm speed" forecast time of maximum surge
t_f - "deep water" forecast time of max. surge
t'_f - "deep-shallow water" forecast time of maximum surge

Table X. "QUALITATIVE", "SURGE SPEED = STORM SPEED" "DEEP WATER", & "DEEP-SHALLOW WATER" FORECAST ERRORS

values of the time that the storm would reach the coast were used, it is believed that the results would not be as good. The errors listed in Table X for the "deep water" and the "deep-shallow water" methods are the minimum errors which resulted, which in most cases occurred when the forecasts were made for hurricane positions which were quite close to the coast.

The best results were obtained from letting the surge travel at the speed of the storm. However, it is felt desirable to have a technique which is independent of parameters which have to be forecast. Therefore a further comparison of the "deep water" and "deep-shallow water" methods will be discussed.

For these techniques, Tables XI and XII show the number of cases falling within the error limits indicated, for forecasts made when the hurricanes were at different distances from the coastline. For forecasts made when the storm was within 300 nautical miles of the coast fairly reliable results were obtained. Forecasts made when the storms were further than 700 miles from the coast appear to have little reliability. Making a forecast when a hurricane is within 300 miles of the coast seems to leave little time for action; however, for the nine storms considered in this study, the least time available, from when the storm was 300 miles distant to the occurrence of the maximum surge, was 23 hours. For a hurricane travelling at 30 knots, about eight hours would elapse between a forecast made when the storm was 300 miles at sea, and the time of the maximum surge.

A comparison of Tables XI and XII show that some improvement over the "deep water" method is made by applying the shallow water correction. However, the results obtained from "deep-shallow water" forecasts are

MAXIMUM DISTANCE TO STORM WHEN FORECAST IS MADE	NUMBER OF CASES WITHIN ABSOLUTE ERROR LIMITS INDICATED			
	<4 hrs	4-12	12-24	>24 hrs
300 n.mi.	8	4	2	1
500 n.mi.	9	6	6	4
700 n.mi.	11	6	6	9
900 n.mi.	11	7	8	12

Table XI. "DEEP WATER" TIME ERRORS

MAXIMUM DISTANCE TO STORM WHEN FORECAST IS MADE	NUMBER OF CASES WITHIN ABSOLUTE ERROR LIMITS INDICATED			
	<4 hrs	4-12	12-24	>24 hrs
300 n.mi.	10	4	2	0
500 n.mi.	12	6	5	6
700 n.mi.	12	8	5	8
900 n.mi.	12	10	6	10

Table XII. "DEEP-SHALLOW WATER" TIME ERRORS

not strikingly better than those derived from use of the "deep water" technique. Further, it is a great deal more dangerous to forecast the maximum surge one hour late than even several hours early, and with the "deep-shallow water" method many late forecasts were obtained. For these reasons it is not felt that the extra work involved in the "deep-shallow water" technique is worth-while to the practical forecaster.

As can be seen from the development of this forecasting technique there are many possible sources of error. Some sweeping assumptions have been made in the interest of producing a technique which requires a minimum of parameters, and that requires parameters which would be easily available to the forecaster before the arrival of the hurricane. However, from the results of applying the "deep water" method to the nine storms on which it was tested, it appears that the technique is well worth additional testing to determine if it can actually be used in the field.

4. SUGGESTED FUTURE RESEARCH AND CONCLUDING REMARKS

4.1 Height Forecasting.

At present fairly reliable results can be expected from height of maximum surge forecasts made using the NHRP method. It appears that the Kajiura method would give better results than the NHRP technique if it were possible to determine the amplification factor to be applied in a particular forecasting situation. An empirical study of this factor might reveal an accurate and convenient method of applying it.

4.2 Time Forecasting.

The method developed in this study should be tested further to determine its actual usefulness. With more data available, a strictly empirical treatment of the parameters used in this study to forecast the time of the maximum surge might result in a more reliable technique.

The present measurement of the size of the storm, the radius of the 1000 mb isoline, can be quite inaccurate. Perhaps the substitution of some related parameter which maybe more correctly determined would improve the results.

4.3 Data.

In conclusion it is well to point out that the main thing that has held back worthwhile study in this field has been the lack of data. There is available a wealth of hurricane data for almost all parameters imaginable except for the high waters associated with the storm.

This problem may soon be alleviated, for by the end of 1960 the U. S. Weather Bureau expects to publish a series of storm surge charts. Some of the data for this study were taken from advance copies of these charts. These charts show the storm track geographically and relative

to the maximum surge profiles which are drawn for a series of stations along the coast. Further, the Climatological Data publication has started publishing similar surge data in a less elaborate form for current storms.

With these additional data available we may expect great strides toward accurate forecasting of all aspects of the surge problem in the future.

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APPENDIX I

THE CONNER, KRAFT, AND HARRIS HEIGHT FORECASTING METHOD

In April 1957, W. C. Conner, R. H. Kraft and D. Lee Harris [2] presented a quantitative technique for forecasting the maximum height of the storm surge.

In the method, which was similar to one which had been developed for local use by the New Orleans Weather Bureau Office several years previously, a single parameter was selected which would cover as many of the factors which affect the maximum surge as possible. A simple storm model was used in which it was assumed that the pressure distribution depended only on the distance from the center of the storm. In such a model the maximum wind speed, V_{max}, depends on the pressure deficiency as expressed by:

$$V_{max} = K(p_n - p_o)^{1/2}$$

where: K = constant of proportionality
p_n = pressure at the edge of the storm
p_o = pressure at the center of the storm.

The total setup due to the wind, h, was taken as:

$$h = B\,V_{max}^{2b}$$

where: B & b = constants determined empirically.

These two equations were combined to obtain a suitable form for calculation of the maximum surge height based on pressure. It had been found that the pressure at the edge of the storm could be considered constant for all storms. In this case a value of 1019 mb was selected for p_n, and b was chosen to equal one. B was evaluated using data for Gulf of Mexico hurricanes and the final resulting equation took the form:

$$h_{max} = 0.154(1019 - p_c)$$

where: h_{max} = maximum storm surge height.

Although based on Gulf coast data, this method was tested using Atlantic coast hurricanes and it was found satisfactory except for storms which travelled parallel and close to the coastline.

A graph of the final forecasting equation was presented which the forecaster could enter with the lowest pressure in the hurricane to obtain the maximum storm surge height. A copy of this forecasting curve is included here as Figure 11.

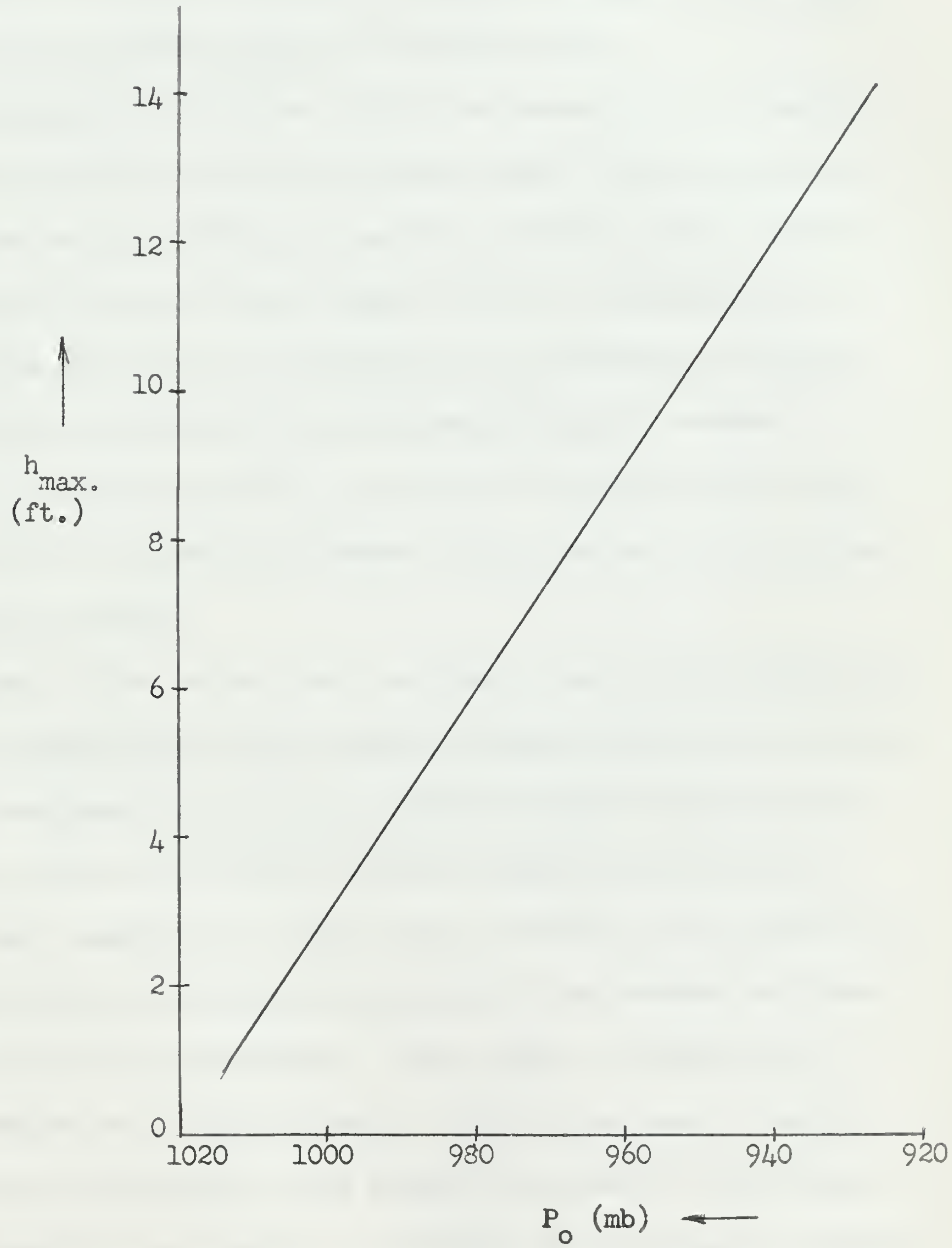

Figure 11. CONNER, KRAFT, AND HARRIS HEIGHT FORECASTING GRAPH

APPENDIX II

THE HOOVER HEIGHT FORECASTING METHOD

Concurrently with the development of the Conner, Kraft and Harris study (Appendix I), Robert A. Hoover [7] also developed a technique for forecasting the maximum height of the storm surge.

The development of the Hoover method was essentially the same as for the Conner, Kraft and Harris technique, except that the analysis of the data was handled differently and more data were used. Hoover pointed out that since the actual highest tide may frequently go unobserved at tide stations, the regression line determined by Connor, Kraft, and Harris was biased toward underestimating the maximum. Furthermore, in the previous study many sets of hurricane data could not be used since the tide gages became inoperative before the maximum surge height was reached.

For as many storms as data were available, Hoover constructed profiles of the surge height versus lateral distance from the storm track. The data was weighted in an effort to obtain profiles which would not reflect local effects, and where data were missing the profile was estimated. Upon examination of these surge profiles it was found that along certain parts of coastline they resembled one another more than along other parts of the coastline. These groups of profiles were therefore combined on a regional basis. One of these sets of surge profiles, that for hurricanes which entered the coasts of North Caroline, South Carolina, and Georgia, is included in this study as Figure 12.

Hoover used these profiles to interpolate the actual highest surge in cases where data were missing or doubtful. From the data thus obtain-

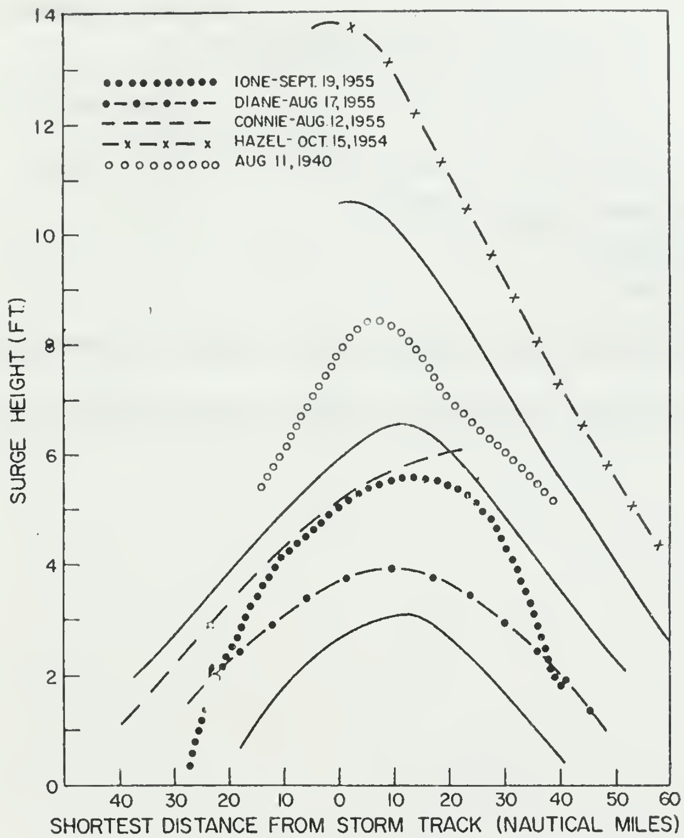

Figure 12. —Surge profiles of the hurricanes which entered the coasts of North Carolina, South Carolina, and Georgia. [7]

ed two regression lines of pressure and maximum surge height were determined, one for the Atlantic coast and another for the Gulf coast. The expressions for these two regression lines were given as:

Atlantic coast;

$$h_{ext} = 0.198\,(1006 - p_o)$$

Gulf coast;

$$h_{ext} = 0.151\,(1032 - p_o)$$

where: h_{ext} = max. surge height

p_o = lowest pressure at center of storm

These two regression lines, which may be used by the forecaster to determine the maximum surge height, are shown in the present study as Figure 13.

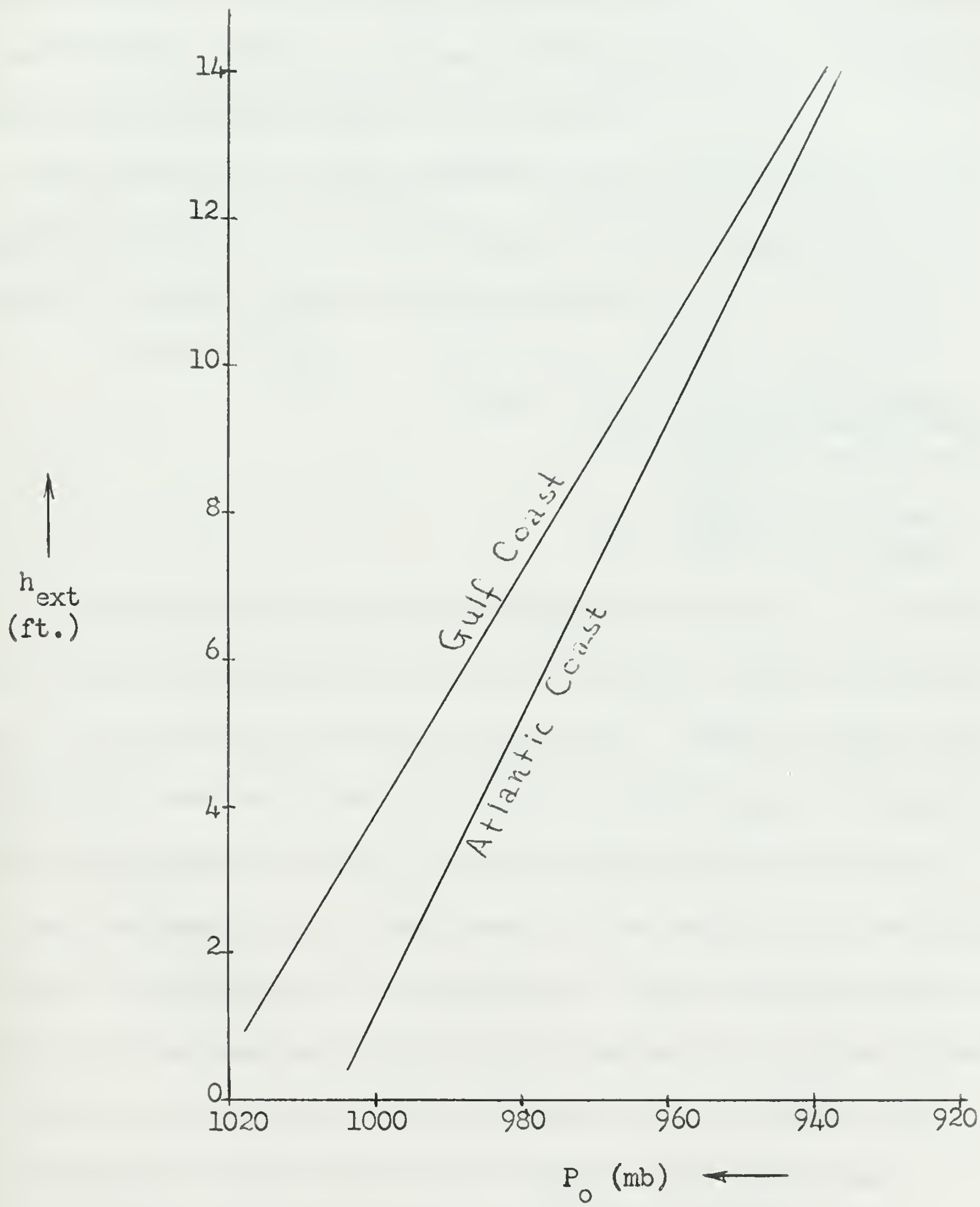

Figure 13. HOOVER HEIGHT FORECASTING GRAPHS

APPENDIX III

THE NATIONAL HURRICANE RESEARCH PROJECT INTERIM HEIGHT FORECASTING METHOD

In August of 1959 the U. S. Weather Bureau officially published "An Interim Hurricane Storm Surge Forecasting Guide" [6]. The largest part of this report was devoted to the presentation of a method for forecasting the maximum height of the surge.

In the development of this method it was assumed that the storm surge height depends on the wind speed, the fetch length, and the depth of water. The basic equation that was used is:

$$h \propto V^2 L/D$$

where:
- h = storm surge height
- V^2 = effective wind stress directed toward the shore
- L = length of the fetch
- D = depth of the water.

It was further assumed that the effective wind stress was related to the pressure deficiency, $(p_n - p_o)$. A constant value was assumed for p_n, the pressure at the edge of the storm. Additional data, more reliable than previously, were available for this study. A value of 1025 mb. was determined for p_n by a least-square fit of the data. It was found that making use of the length of the fetch, L, did not improve the results sufficiently to be considered. Several parameters were considered for determination of the depth of the water. The most effective was found to be the distance from the shore to the 50-fathom curve.

The equation which resulted from these considerations was:

$$h = 0.06213 (1025 - p_o)^{1.1328} S^{0.0663}$$

where:
- p_o = central pressure of the storm
- S = distance between the shore and the 50-fathom depth contour.

This equation was plotted in the form:

$$h = \Theta f(p_c)$$

where: Θ = relative storm surge potential (depends on off-shore depths)

$f(p_o)$ = a function of the central pressure.

A map was provided, shown in this study as Figure 14, which showed values of Θ for the Atlantic and Gulf coasts. A storm surge prediction chart was developed which gave values of surge height versus Θ and p_o. This chart is shown here as Figure 15.

To make a prediction of the maximum height of the storm surge the forecaster obtains a value of Θ from the Map of Relative Storm Surge Potential using the storm track, and then enters the Storm Surge Prediction Chart with this parameter and the lowest pressure in the storm to obtain the height.

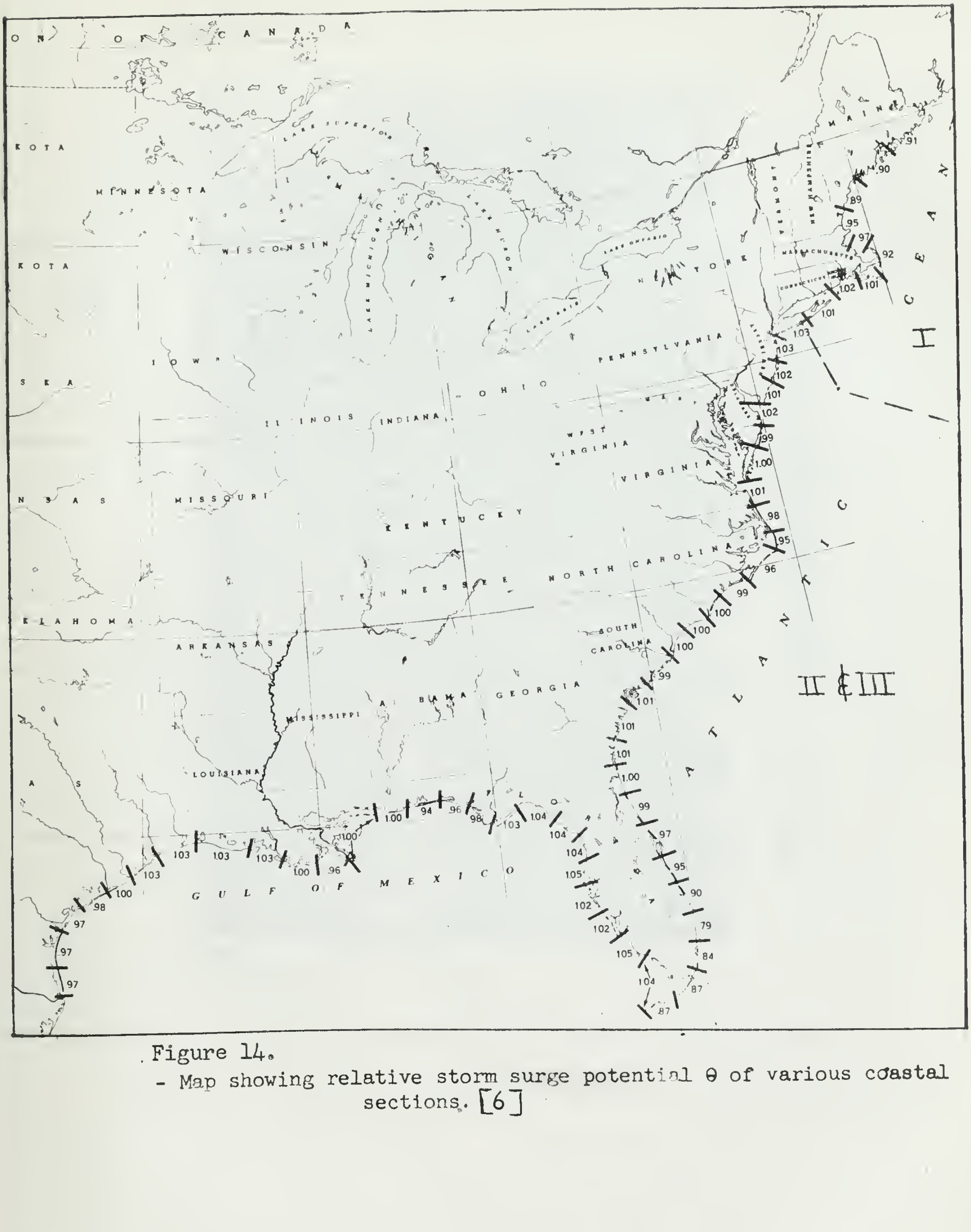

Figure 14.

- Map showing relative storm surge potential θ of various coastal sections. [6]

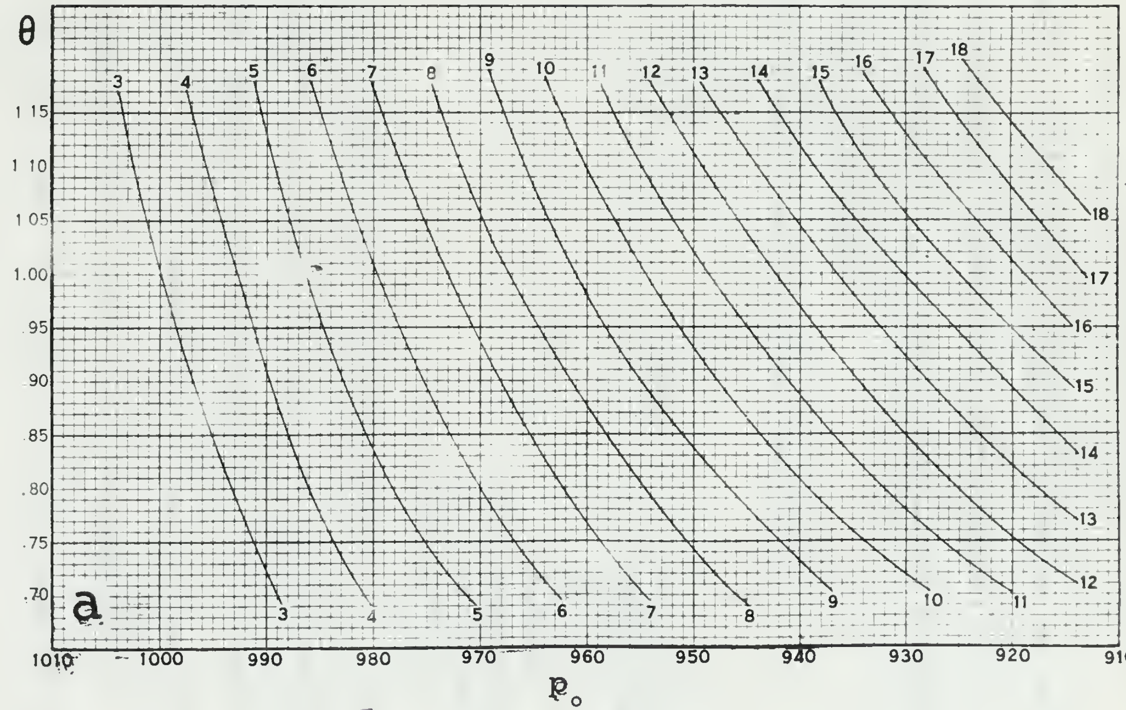

Figure 15. NATIONAL HURRICANE RESEARCH PROJECT [6]
STORM SURGE PREDICTION CHART

APPENDIX IV

THE KAJIURA HEIGHT FORECASTING METHOD

In December of 1959 Kinjiro Kajiura published an extensive study of all the phases of the storm surge problem [8]. A part of Kajiura's work includes a suggested technique for forecasting the maximum height of the storm surge.

The basic equation used in this study was:

$$\eta = \frac{r a'}{\rho g} \Delta p^*$$

where: η = maximum storm surge height
r = dynamic amplification factor
a' = constant depending on the station
ρ = constant density of water
g = acceleration due to gravity
Δp^* = intensity of the storm.

Values of a' were found that covered two rather long sections of the Atlantic coastline, one extending along the New England Coast southward to Montauk, New York; and the other extending from Long Island to the Florida peninsula. When combined with ρ and g these values were 0.14 for the New England region, and 0.2 for the remainder of the Atlantic coast. For the Gulf coast the value of these combined constants was not determined but it was believed to be larger than for the Atlantic coast regions due to the existence of a shallow and wide shelf.

The factor of dynamic amplification was not defined for particular forecasting situations by Kajiura. It was stated that r lies between 1 and 2, and for realistic situations it would seem to be around 1.5 to 2 if the storm moved almost perpendicular to the coastline, over a wide continental shelf, and if the speed of storm movement was suitable. The results of a previous determination of the dynamic amplification factor

by Reid in 1956 for a theoretical one-dimensional model were given. For this one-dimensional case r was somewhere around 1.5 - 2.0. Kajiura further stated that the amplification factor for two dimensional models is a little smaller than for the one-dimensional case. There were not enough data available at the time that this method was developed to determine the amplification factor on an empirical basis.

An approximate expression for Δp^* was taken as:

$$\Delta p^* = 0.55(1015 - p_o)$$

where: p_o = lowest central pressure.

This expression can be combined with the basic equation to give:

$$\zeta = ra[0.55(1015 - p_o)]$$

where: a = constant combining a', ρ, & g.

From this last equation a curve (or series of curves) for the particular region determined by the constant, a, could be drawn if the value (or series of values) of r were known. Two such graphs could be used to forecast the maximum height of the surge.